

Cloud Radar Observations at Kennedy Space Center for the ABFM Experiment

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Abstract

A high-sensitivity, high-resolution millimeter-wave cloud radar was operated at Kennedy Space Center (KSC) in February 2001 as part of the Airborne Field Mill (ABFM) project to study cloud electrification processes and to examine the possibility of safely relaxing some lightning launch commit criteria (LLCC) regulations. The radar was a 35-GHz system with scanning, Doppler, and polarization-diversity capabilities. In spite of prevalent severe drought conditions, useful coordinated measurements with radar, aircraft, and field mills were collected on 03 February 2001. The cloud radar and aircraft data confirmed that a stratiform cloud layer over KSC on this day violated the LLCC “thick cloud” rule because it was more than 4500 ft thick and it extended into the 0 to -20° C temperature interval. Although the *in-situ* particle sampling documented the co-existence of water droplets and ice particles in this cloud, including some centimeter size snowflakes, airborne and ground-based field mills detected only very weak electrical fields that were generally less than 300 v/m. Thus, the threat of triggered lightning was minimal and the thick cloud rule would probably have needlessly prevented a launch in this case. Of course, many additional cases are needed to determine whether the thick cloud rule is overly conservative in general. The detailed cloud radar data were also compared with much coarser data from the WSR-74C precipitation radar at Patrick AFB that is used operationally in launch decisions. Comparisons on two days indicate that the precipitation radar is useful for detecting non-precipitating clouds over KSC and delineating their boundaries if their reflectivities exceed about 5 dBZ. Weaker clouds over KSC either pass undetected by the WSR-74C radar or determinations of their altitudes and thicknesses are obscured or degraded by clutter and noise.

1. Introduction.

Range operations of NASA's Kennedy Space Center (KSC) at Cape Canaveral, Florida, are commonly impacted by a variety of weather hazards, and the possibility of lightning strikes to launch vehicles and spacecraft payloads is a very grave concern. Detailed safety regulations have been established to operationally assess these weather hazards and to delay or scrub rocket launches when conditions warrant. The impacts of these weather-related restrictions on range operations are substantial (e.g. Hazen et al. 1995; Garner 2001).

The Airborne Field Mill (ABFM) project (Merceret and Christian 2000) is a research experiment designed to study processes that produce electrified clouds and to reassess various Lightning Launch Commit Criteria (LLCC) in use at KSC, as prescribed by Krider et al. (1999). The experiment conducted in 2000 and 2001 at KSC, primarily involved a cloud physics research aircraft, a network of ground-based electric field mills, and operational weather surveillance radars. In February 2001 the project also included high-resolution observations of clouds over KSC by a 35-GHz cloud radar from NOAA's Environmental Technology Laboratory (ETL). The experimental plan included using the visiting cloud radar to evaluate cloud condition information provided by the permanent, coarse-resolution, operational weather radars. Detailed observations by the cloud radar were also intended to guide the airborne penetrations of the cloud physics aircraft and provide a clearer context for synthesizing the aircraft and ground-based field mill measurements into case studies of cloud electrification processes.

The February experiment was scheduled to address the LLCC's "thick cloud rule", which, for fear of triggered lightning, prohibits launches if an overhead cloud layer exceeds 4.5 kft in thickness and any portion of it is between 0° C and -20°C. It is thought that this rule may be overly restrictive because cloud layer thickness may be only poorly correlated with lightning development. Cloud thickness is also difficult to assess with the available operational weather surveillance radar data. Thus, in-situ observations of cloud base and cloud top heights by weather reconnaissance aircraft are generally required for this assessment. For these reasons, a revised rule may be desirable.

Unfortunately, Florida was suffering through a prolonged extreme drought in February 2001. Consequently, the ABFM obtained far less useful data than expected. Lightning was non-existent, rain was rare, and clouds were scarce. Drought conditions produced widespread wildfires and thick smoke over central Florida for much of the month. The research aircraft conducted only one flight through clouds over the ETL radar. However, these clouds on 03FEB01 did meet the thick cloud criteria, and electric field mill measurements indicated very low electric field strengths across the area, indicating minimal chance of triggered lightning. No natural lightning was observed anywhere within central Florida on this day. Thus, this was a case where the thick cloud rule probably would have unnecessarily prevented rocket launches. Although generalizations must not be drawn from a single case, it is examined and documented here for future reference.

Comparisons of radar echoes detected by the cloud radar and the WSR-74C precipitation radar used in the LLCC decision process are another focus of the present study. The objective is to use the “visiting” ETL cloud radar data to better understand how well the permanent WSR-74C radar is capable of revealing the desired information about clouds over KSC. Data from these two radars are compared for the thick cloud case of 03FEB01 and for 13FEB01 when persistent cirrus and intermittent stratus layers were present over KSC. Neither of these kinds of clouds on 13FEB01 represents a lightning hazard, but the additional comparisons help to further assess how well the WSR-74C detects non-precipitating clouds over the Cape.

2. The NOAA/K Cloud Radar

ETL’s 35-GHz (Ka-band, 8.7-mm wavelength) NOAA/K radar is a state-of-the-art research instrument designed to provide extensive, high-resolution information about the structure, kinematics, and microphysical characteristics of nearby clouds. Its operating characteristics and measurement capabilities are described by Martner *et al.* (2002a). Table 1 summarizes primary features of the radar, which is normally operated by a crew of two people. The system is transportable to field experiments on its own flatbed trailer and has full scanning capabilities. Its Doppler measurements provide information about internal cloud airflow patterns and particle fall speeds and its dual-polarization capabilities have been extensively developed to identify cloud hydrometeor types (*e.g.* Reinking *et al.* 1997). More than a decade of innovative cloud research conducted with NOAA/K has inspired the more recent development of several new cloud radars by various organizations. This includes the millimeter-wave cloud radar (MMCR), designed by NOAA/ETL as a continuous, unattended cloud profiler for the U.S. Department of Energy (Moran *et al.* 1998) and a new unattended polarization-diversity radar and radiometer system being designed by ETL for the FAA to detect aircraft icing conditions in the vicinity of airports (Reinking *et al.* 2001).

On short notice, ETL was enlisted to have its NOAA/K radar join the ABFM experiment of February 2000. The radar was transported from Colorado and located at a KSC C-band rocket-tracking radar facility about 1 km east of the Shuttle Landing Facility (SLF) and 5 km north-northwest of the Vehicle Assembly Building (VAB). Figure 1 shows photographs of NOAA/K at this site. The location was well within the permanent KSC network of ground-based electric field mills and within 25 km of all launch pads on the Cape. From this vantage point, the NOAA/K was available to provide highly detailed observations of clouds over the Cape for examination within the context of the field mill network measurements and the focused in-situ cloud sampling by overpasses of the University of North Dakota (UND) Citation research aircraft. An electric field mill from the University of Arizona was also temporarily installed adjacent to the radar. Scan images from the radar were posted on the Worldwide Web in near realtime, and radio communications between the radar crew, the research aircraft, and the project command center were established to facilitate experiment operations. The radar was available for data collection at KSC from 01FEB01 through 22FEB01.

Table 1. Characteristics of the NOAA/K Cloud Radar as Used in the ABFM 2001.

<i>Major Capabilities</i>	scanning, Doppler, polarization-diversity, transportable
<i>Primary Uses</i>	observations of structure, airflow and composition of clouds, drizzle, snowstorms of any intensity, and very light rain
<i>Frequency</i>	34.66 GHz (wavelength = 8.6 mm, Ka-band)
<i>Peak Transmit Power</i>	80 kW (average. power = 40 W)
<i>Antenna</i>	1.8-m center-feed dish (1.2-m dish with offset Cassegrain feed and phase retarding plate also available),
<i>Beam Width</i>	0.3 deg.
<i>Pulse Length</i>	0.25 microsec. (resolution = 37.5 m)
<i>PRF</i>	selectable (2000/s typical); double-pulse method used to extend Nyquist (folded velocity) limits
<i>Scans</i>	PPI, RHI, sector, fixed beam, all with elevations through zenith and below horizon; scan rates up to 30 deg/s.
<i>Sensitivity</i>	approx. -35 dBZ at 10 km range with 1.8-m antenna
<i>Polarization</i>	45-deg. slant linear; various others also available; co-polar and cross-polar returned signals simultaneously received.
<i>Doppler Processing</i>	pulse pairs; time series also available for Doppler spectra.
<i>Data System</i>	VME-based with DSP and SPARC workstation
<i>Platform</i>	15-m flatbed trailer, or 2 seacontainers for overseas operations.
<i>Reference</i>	Martner <i>et al.</i> (2002a)



**NOAA/K Cloud Radar
at Kennedy Space
Center, Feb. 2001**

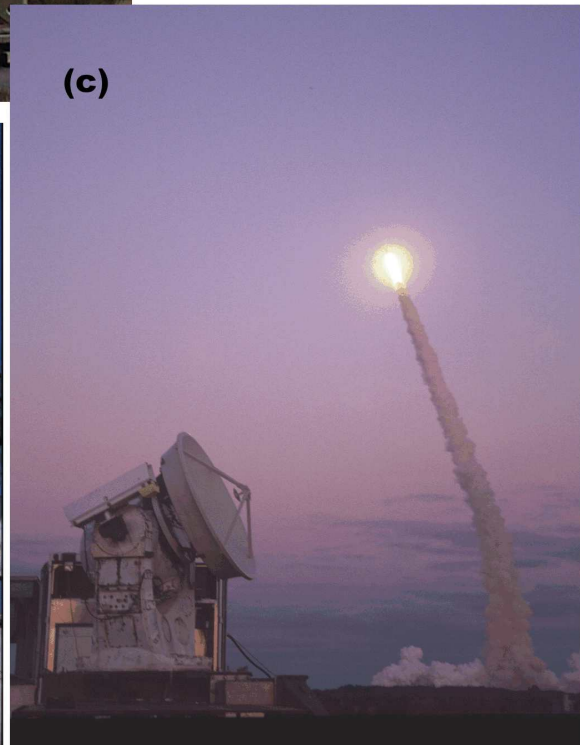


Figure 1. The temporary deployment on the NOAA/K cloud radar from NOAA/ETL at Kennedy Space Center: (a) radar and its flatbed trailer, (b) the radar's 6-ft-diameter antenna, (c) the Space Shuttle Atlantis launch at sunset on 7FEB01. Photographs by Brooks Martner.

3. Restrictions

The ABFM desired the use of a scanning cloud radar that could provide coverage across the Cape Canaveral area to assess cloud conditions over the launch pads and outward along the initial rocket trajectories as they rise through the troposphere. ETL's NOAA/K radar readily detects clouds as weak as about -35 dBZ at 10 km range, but the detection capability diminishes by 6 dB for each doubling of range. Thus, normally, the radar is not used to collect data beyond about 25 km, because many weak non-precipitating clouds escape detection at longer ranges. Thus, it is highly desirable to locate the radar close to the primary area of interest. In the ABFM experiment, the site selected for NOAA/K was about 1 km east of the SLF and 6-8 km west of the Shuttle launch pads, 39B and 39A, and was surrounded by electric field mill sites. In ABFM operations, a 20-km maximum range was used, within which, the radar does an excellent job of detecting and measuring the characteristics of most visible clouds. From its location, the radar could (in theory) observe clouds over almost the entire KSC and Cape Canaveral Air Station region.

In practice, however, the radar's operations were constrained by NASA and U.S. Air Force frequency management regulations. These regulations prohibit transmissions at frequencies above 18 GHz, that irradiate buildings and structures with peak-power energy levels exceeding an electric field strength of 1 volt per meter. The regulations are designed to insure the integrity of electronic devices on launch vehicles, and are vastly more restrictive than occupational health safety standards that are based on average power levels. The 1 v/m threshold represents a tiny amount of power density (0.0027 W/m^2).

NOAA/K radar's transmitter produces 80 kW of peak power, concentrated into a narrow beam by a high-gain antenna. Within the central beam axis (main lobe), its peak power greatly exceeds the allowable threshold across the entire Cape area from the radar's site near the Shuttle Landing Facility. Thus, NOAA/K was not allowed to scan at elevations low enough to point directly at any structures. According to power calculations and field measurements of the radar's side lobes, it was determined that the minimum acceptable elevation angle was 14 degrees above the horizon. Mechanical and software brakes were installed to prevent the radar from scanning below 18 degrees during the ABFM experiment. This limitation precluded the possibility of observing low-altitude clouds that were located more than a few kilometers away (horizontally) from the radar site. Mid-level and high-altitude cloud observations were not significantly impacted by the elevation angle restriction.

Additional "quiet time" regulations prevented the radar from transmitting at all during certain kinds of range operations, including launches, Shuttle landings, payload ground transport, and Shuttle training aircraft operations. The NOAA crew adhered to all of these regulations. The quiet time restrictions also prevented using NOAA/K to provide high-resolution observations of the drift, dispersion, and shapes of particles within rocket launch exhaust plumes, as has been done on a coarser basis using the National Weather Service's much more distant WSR-88D (NEXRAD) precipitation radar at Melbourne, Florida (Parks and Rosati 2000).

4. Thick Layer Cloud Case of 03FEB01

The Setting and Operations

On 03FEB01 a weak frontal system moved into central Florida creating a stratus overcast and cold, northerly winds at KSC. At times, the clouds produced drizzle and very light rain. The morning radiosonde marked the 0C and -20C levels at 4 and 7 km MSL, respectively. The NOAA/K radar scans showed that the stratus layer was too shallow to reach the freezing level in the morning. The radar monitored the clouds throughout the day and its echo images were displayed in near realtime on the Worldwide Web. By mid-afternoon the images showed that the clouds had deepened, reaching the -5 C level at 4.5 km MSL. This deepening was associated with a more banded appearance of cloud echoes than was seen earlier by the WSR-74C radar at Patrick AFB and the NEXRAD radar at Melbourne.

The University of North Dakota Citation was launched from Titusville at 20:40 UTC, based on the NOAA/K observations. The Citation conducted 18 penetrations of the cloud over the radar vicinity on flight track legs oriented approximately north-south before landing at 22:55. The cloud penetrations were all between 4.5 and 3.5 km MSL (-5 C to +1 C). This was the Citation's first attempt at an operational flight for the February experiment and, unfortunately, some of its particle sampling probes were inoperative or failed during flight. Therefore, knowledge of the hydrometeor characteristics is limited. During the Citation overpasses, NOAA/K conducted a continuous series of RHI "dome" scans every minute that provided vertical cross-sections through the sky at azimuth increments of 30 degrees. The 155/335-degree azimuth scans most closely paralleled the aircraft flight track legs; one such scan was obtained approximately every 6 minutes. The radar was fully operational and suffered no problems during the mission.

Drizzle fell at the NOAA/K site during parts of the 2-hour flight. The total accumulation measured with a gauge at the site was no more than 0.04 inches, which corresponds to an average rain intensity of only 0.5 mm/hr. Maximum observed reflectivity factors were approximately 25 dBZ in drizzle and virga streamers and within the melting layer bright band. Thus, this cannot quite be classified as precipitation-free case, but the drizzle produced by the cloud may have been deemed too light to warrant suspension of launch activities based on precipitation criteria. However, the cloud layer, as observed by NOAA/K, definitely met the criteria for suspension by the thick cloud rule LLCC criteria. Yet, as will be shown, the airborne and ground-based electric field mills measured only very weak electric fields, suggesting no real threat of lightning existed in this cloud.

The Radar Context

Figure 2 shows an example of PPI scans from the C-band (5.5-GHz, 5-cm-wavelength) WSR-74C radar at Patrick AFB during the Citation flight. The figure provides the larger horizontal context for interpreting detailed data from the NOAA/K cloud radar (designated by the red X in

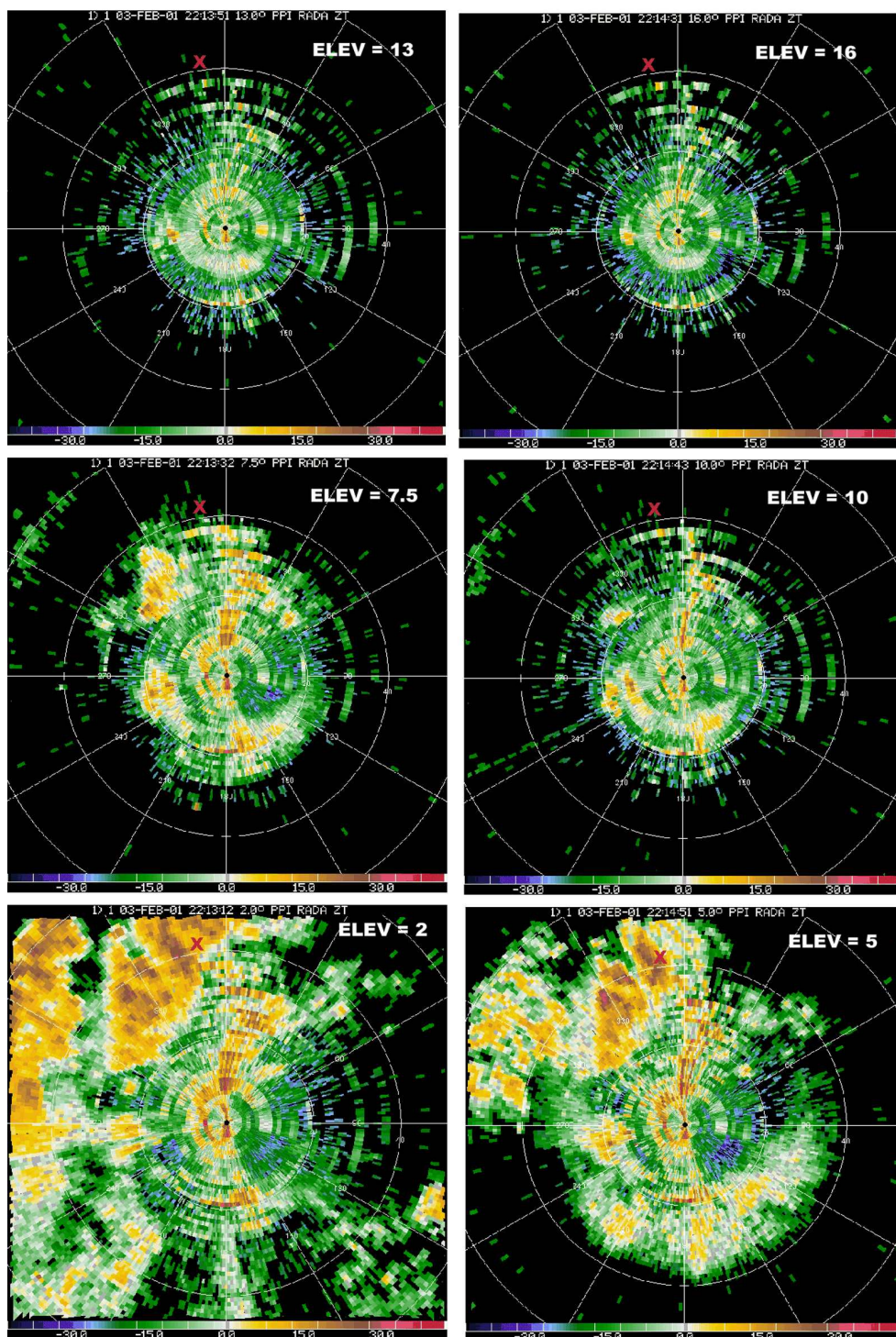


Figure 2. PPI images of reflectivity from six elevation-angle scans of the WSR-74C radar at approximately 2213 UTC on 03FEB01. Range rings are drawn at 20-km intervals. The location of the NOAA/K cloud radar at azimuth = 350 deg. and range = 42 km is indicated by the red X.

near the top of each PPI image), which was 42 km north of the WSR-74C radar. The lower elevation scans of the WSR-74C show the somewhat banded and cellular appearance of the echoes, characteristic of embedded convection within widespread stratiform clouds. The maximum reflectivity was approximately 30 dBZ, which suggests drizzle or very light rain fell in a few small pockets within the widespread cloud that otherwise produced only virga. The figure also shows extensive and strong ground clutter targets across much of the region. The coastline's contour is clearly discernible north and south of the Patrick AFB, even in scans as high as 10 degrees. This prevalent clutter makes it more difficult to use these data to identify cloud conditions over the Cape, unless the cloud and rain echoes are relatively strong. In general, the smaller antennas and shorter wavelengths of cloud radars are less prone to ground clutter contamination than is common for C-band and S-band radars (Kropfli and Kelly 1995).

Figure 3 shows examples from the NOAA/K radar's realtime display of RHI scan images oriented approximately parallel to the Citation flight legs. Selected scan images, such as these, were available from NOAA/K on the Worldwide Web in near realtime during the ABFM to help guide operations. Ordinarily the radar's domer RHI scans would extend from horizon to horizon, but the KSC frequency management restrictions prevented the use of low elevation angles. Nevertheless, the scans reveal the detailed vertical structure of cloud and precipitation echoes in the vicinity of the radar. Clearly, the high-resolution cloud radar images (Figs. 3 and 4) provide a much more detailed and immediately useful picture of cloud conditions in the radar's vicinity than can be inferred from the WSR-74C PPI scans (Fig. 2). A prime purpose for NOAA/K's inclusion in the February campaign is to use its measurements as a "ruler" by which to assess the WSR-74C's routinely-available information about cloud thicknesses and heights. This is addressed in Section 5.

The maximum reflectivity in the scans was approximately 25 dBZ. The existence of a melting layer bright band can be discerned in Figure 3's reflectivity image near 3.7 km above ground level (AGL). In addition to reflectivity, NOAA/K measures Doppler and depolarization parameters at each range gate. Figure 4 shows an example of all three parameters for the RHI scan at 2118 UTC from post-processed data. The presence and altitude of the melting layer is even more clearly defined by the radar's depolarization ratio (DR) data, such as shown in the lower panel of the figure. The DR values and patterns confirm the dominant presence of spherical drizzle drops below the melting layer, and indicate the presence of ice crystals of irregular shapes above it with embedded cloud or drizzle droplets mixed with the ice in some regions. RHI scan images of radial component of Doppler velocity (upper panel, Fig. 4) readily reveal heights of significant wind shear in the clouds. The sharp reversal of wind directions near 1 km AGL from a northerly component flow of the air near the surface to the southerly component flow above it, establishes the height of the advancing cold frontal surface aloft.

But most important for the ABFM, the cloud radar helps determine cloud layer heights and thicknesses. The data in Fig. 4 also show that the mid-level cloud layer echo extended from approximately 3 to 5 km at this time and the melting layer bright band was located about 1 km below the echo top. Thus, requirements for an LLCC "thick cloud" classification were met

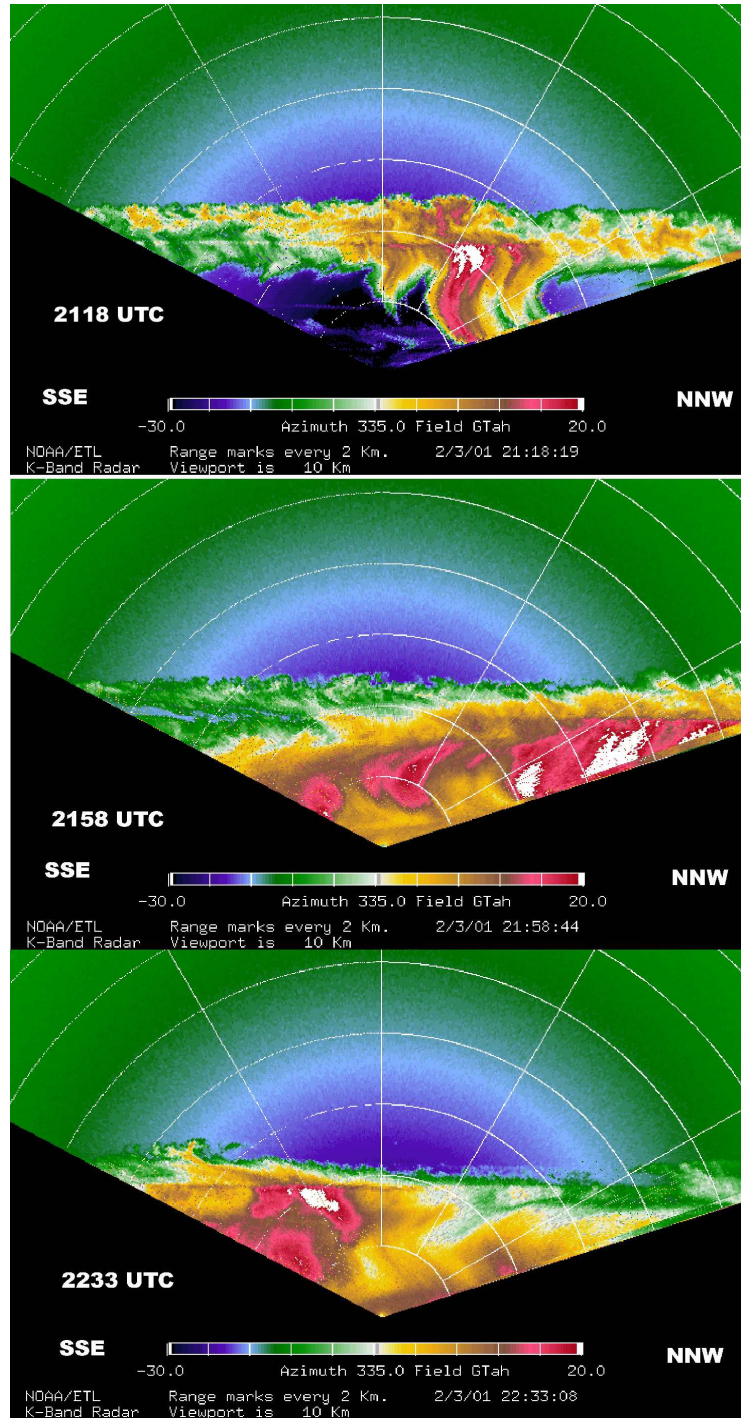


Figure 3. Examples of RHI scan reflectivity images from NOAA/K's realtime display for three times during the Citation flight on 03FEB01. Range rings are drawn a 2-km intervals. Images such as these were posted on the Worldwide Web in near-realtime during the flight.

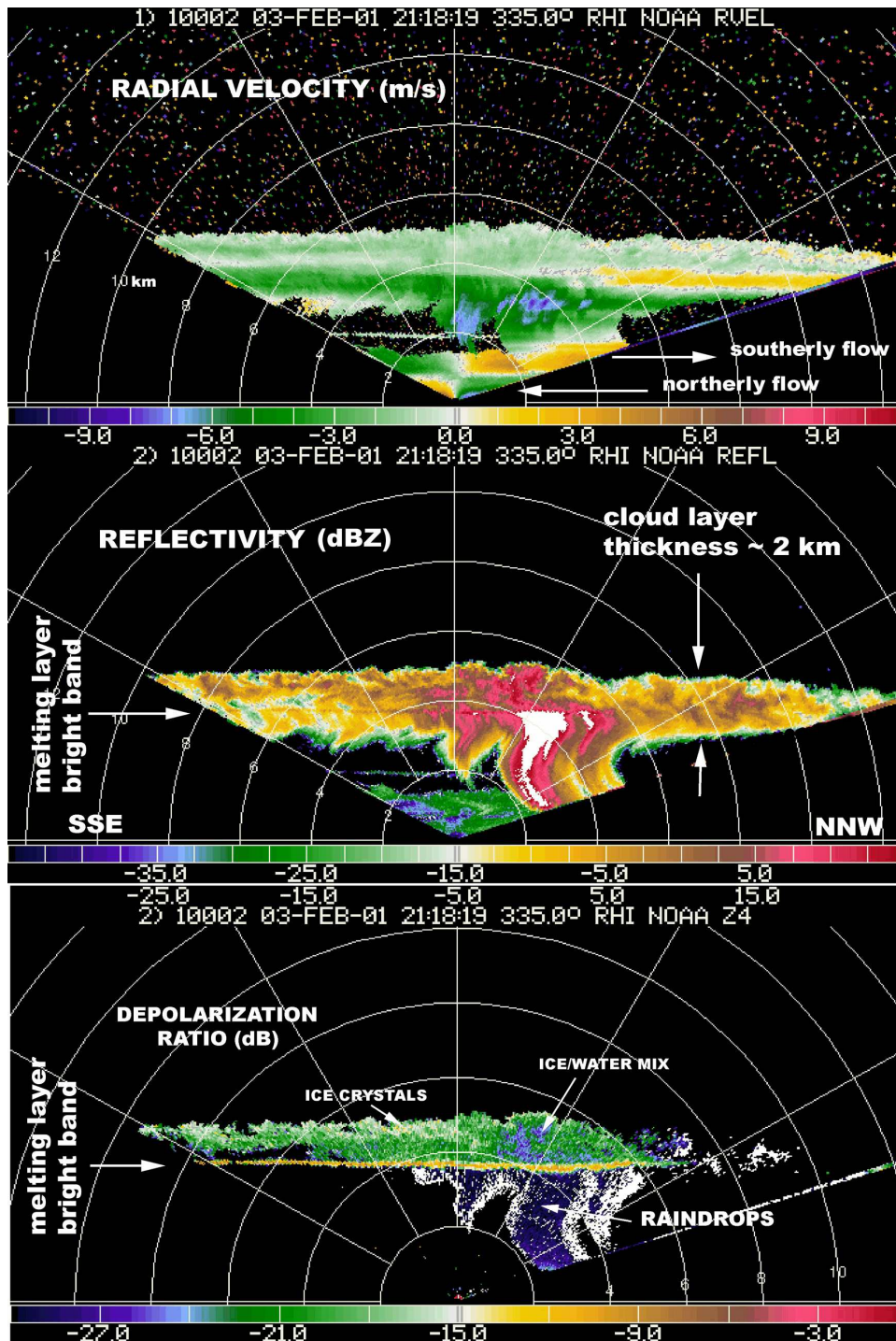


Figure 4. Post-processed data showing velocity, reflectivity and depolarization ratio images from an RHI scan by the NOAA/K cloud radar during the early part of the Citation flight.

because the cloud was more than 4500 feet thick and part of it was within the 0 to -20 °C temperature range. Embedded convection produced streamers of droplets that fell from this cloud into extremely weak stratus layers below 1.5 km. The presence of this spotty virga, drizzle, or very light rain may also have qualified the case for LLCC precipitating condition launch restrictions. At the time of the scan in Figure 4, the research aircraft had just begun its series of passes over the radar.

Aircraft Penetrations

The flight track of the UND Citation is shown in Figure 5. After an initial foray out over the ocean, the pilot began a series of 18 consecutive passes in cloud near the NOAA cloud radar location. The passes occurred between 2130 and 2234 UTC and were oriented approximately north-south. Figure 6 shows an example of a pass that was closely aligned in location and time with an RHI scan from the radar. Air traffic restrictions prevented the passes from extending as far north as was desired and some passes drifted a few kilometers east of the radar. Nevertheless, all 18 passes were made in the immediate vicinity of the radar. By way of radio communication, the NOAA crew provided the aircraft crew with information about echo top heights and other features derived from the cloud radar during the flight. This helped the Citation crew to choose appropriate altitudes for their passes.

As shown in the top panel of Figure 7, the first several passes were made at the -5 °C level (4.6 km AGL), followed by a gradual step-down descent to +1 °C (3.3 km) and then a stepped climb back to -5 °C. Thus, almost the full cloud depth over the radar was sampled during a period of 64 minutes. To illustrate the registration of aircraft and radar measurements, Figure 6 shows the location of the 2215 UTC pass with respect to the nearest corresponding RHI scan from the cloud radar. The airplane was flying at the melting level on this pass.

The *in situ* hydrometeor measurements by the aircraft were limited by the malfunction of some of the probes and other occasional data system problems. However, it is clear that both liquid water cloud droplets and ice crystals were present on nearly every pass. The lower panels of Figure 7 show the particle size and concentration measurements for cloud droplets measured by the Forward Scattering Spectrometer Probe (FSSP). Similar plots in Figure 8 show the same information for ice crystals (presumably) detected by the 1D-C probe. Mean cloud droplet sizes were about 25 microns and concentrations were generally less than 100 cm⁻³. These values are more characteristic of marine than of continental airmass clouds. The mean ice particle size was about 150 microns and concentrations were highly variable from pass to pass. The presence of several large ice crystals or snowflakes was documented by the High Volume Particle Sampler (HVPS), such as in the example in Figure 9. On this pass at -1 °C, silhouettes of numerous millimeter-size irregular crystals or aggregates are recorded; a few of them had maximum dimensions of about 1 cm.

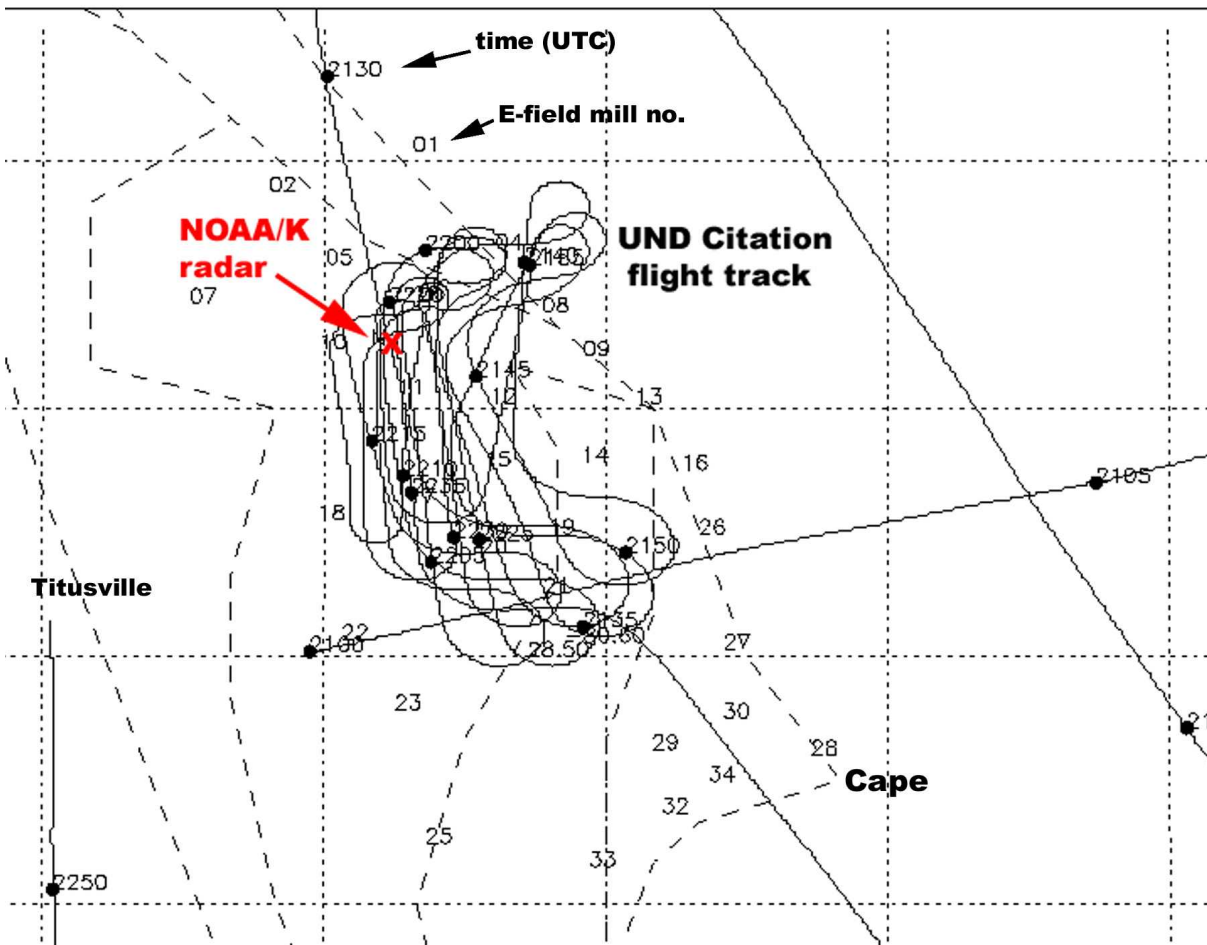


Figure 5. Flight track of the University of North Dakota Citation research aircraft on 03FEB01. Location of the NOAA/K cloud radar is shown by the red X. Locations of the KSC ground-based electric field mills are designated by the two-digit numbers.

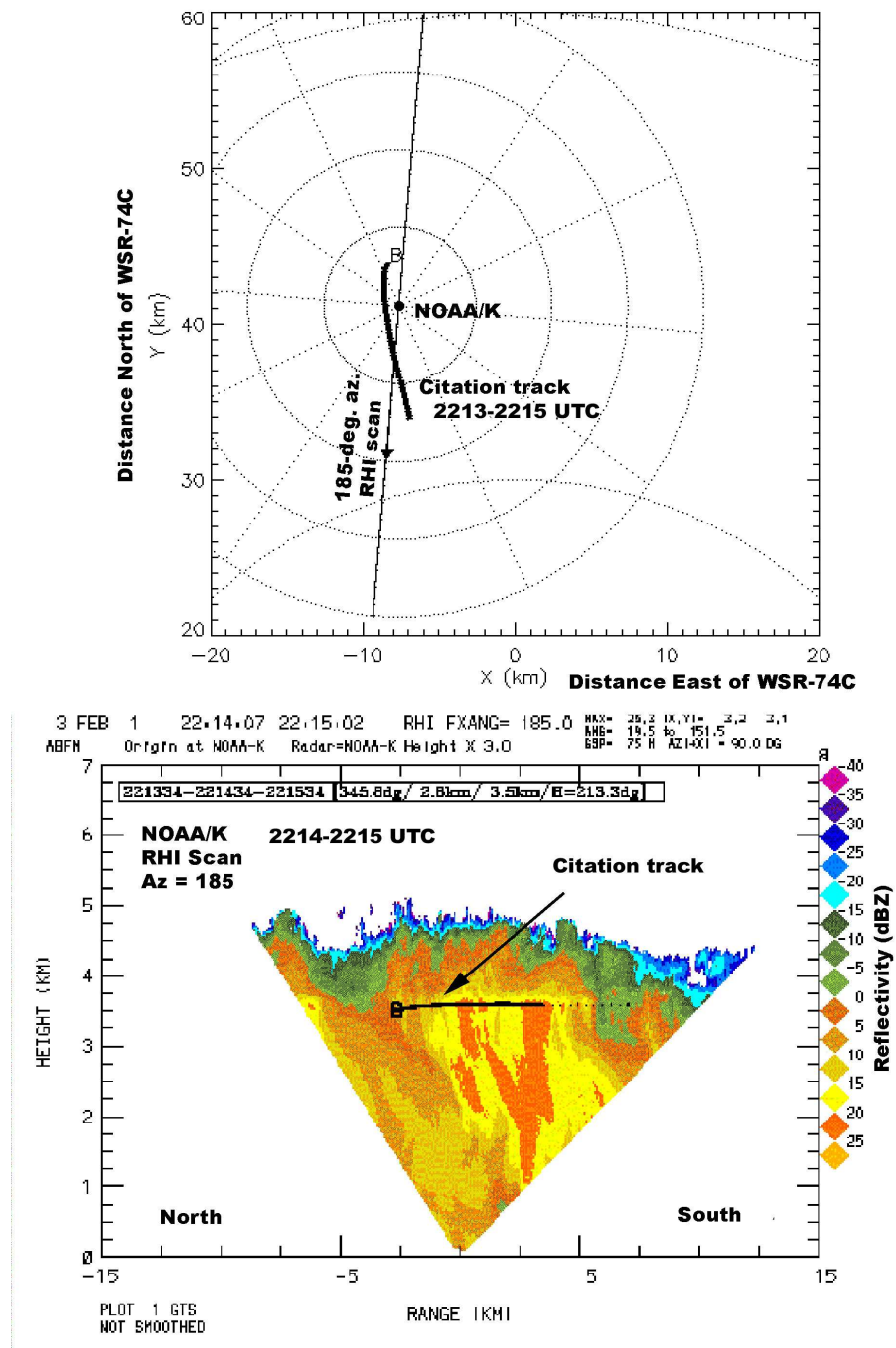


Figure 6. An example of the alignment of a Citation pass and the nearest RHI scan by the NOAA/K cloud radar. Most passes did not line up this closely with the scans, but all were in the vicinity of the radar.

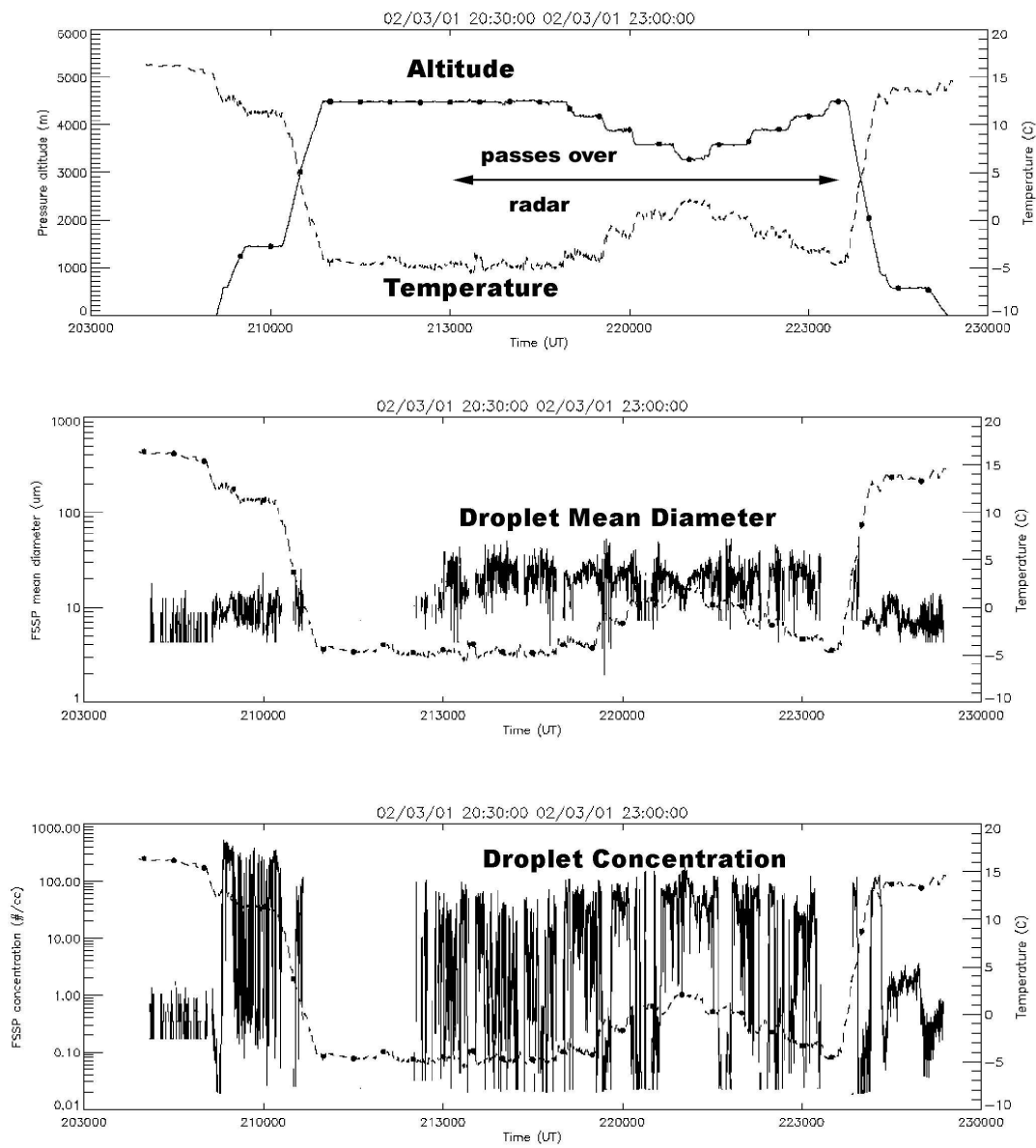


Figure 7. Time series plots of data from the UND Citation on 03FEB01. The top panel shows pressure altitude, temperature, and the period of passes over the NOAA cloud radar. The middle panel shows cloud droplet mean diameter from the FSSP and repeats the temperature trace. The bottom panel shows total cloud droplet concentration from the FSSP and repeats the temperature trace.

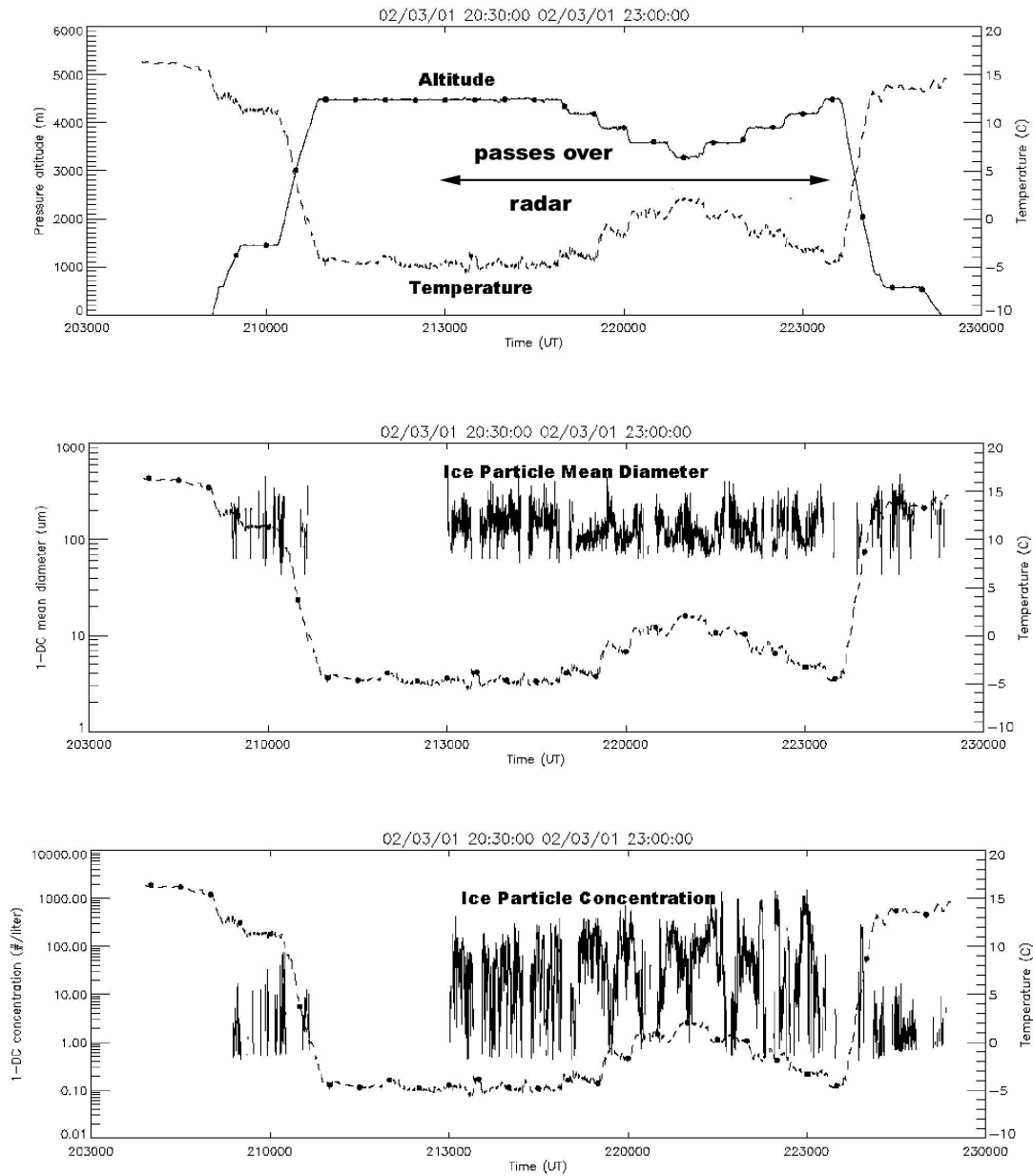


Figure 8. Time series plots of data from the UND Citation on 03FEB01. The top panel shows pressure altitude, temperature, and the period of passes over the NOAA cloud radar. The middle panel shows mean ice particle diameter from the 1D-C probe and repeats the temperature trace. The bottom panel shows total ice particle concentration from the 1D-C and repeats the temperature trace.

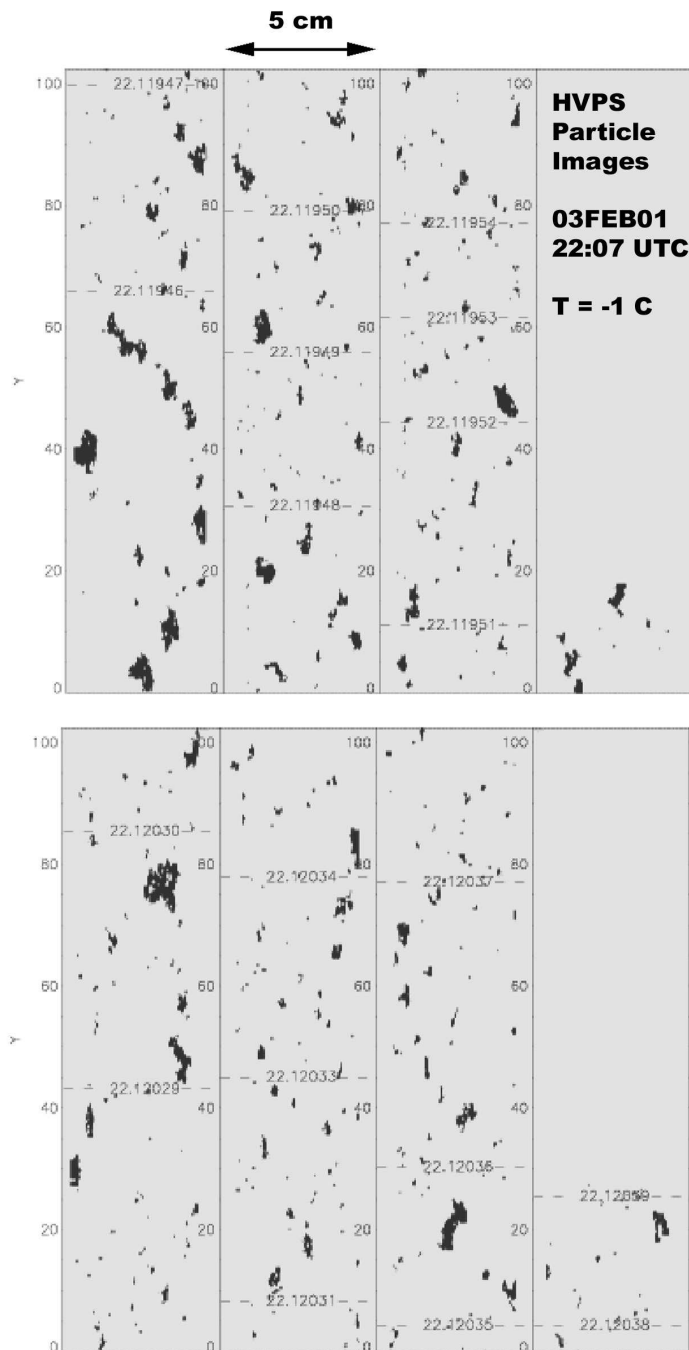


Figure 9. Examples of hydrometeor silhouettes obtained on 03FEB01 by the High Volume Particle Sampler probe on the UND Citation. These images are from 22:07 UTC when the aircraft was flying just above the melting layer over the cloud radar.

Electric Fields

The NOAA cloud radar was located within the KSC network of ground-based electric field mills (see Fig. 5). Operational and research use of the field mill network dates back more than a quarter century (*e.g.*, Jacobson and Krider 1976). The vertical electric field strength during the Citation flight from the three mills in the network closest to the radar are shown in Fig. 10. The measured fields were weak. One mill (#6) briefly measured a field of about 400 Vm^{-1} , but most of the time all three mill registered less than 300 Vm^{-1} . The University of Arizona mill, installed on this day at the cloud radar site, confirmed these very weak readings (Murray, private communication). Similarly weak E fields were detected aloft in the cloud by the Citation (Fig. 11). It is reasonable to conclude that these very weak electric fields presented little or no threat of triggered lightning and no threat of natural lightning strikes. No lightning strikes occurred on this day anywhere in central Florida.

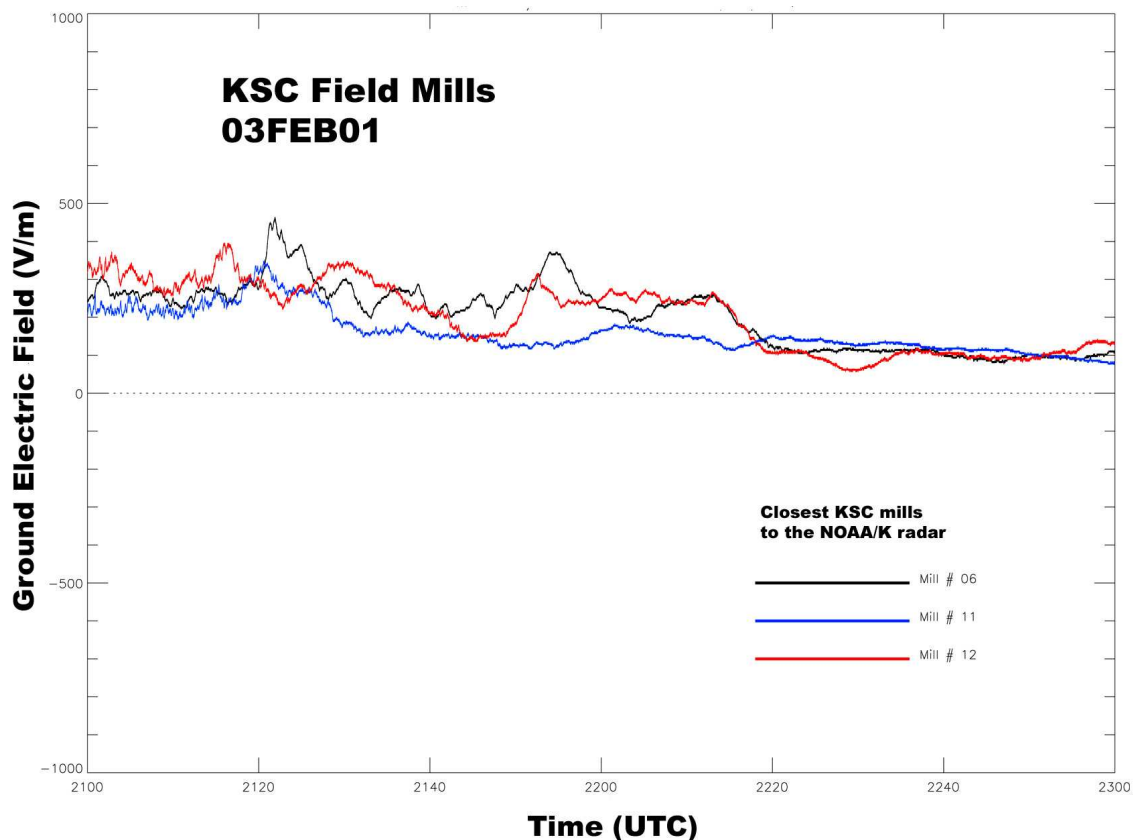


Figure 10. Ground-based electric field measurements from the KSC network of mills.

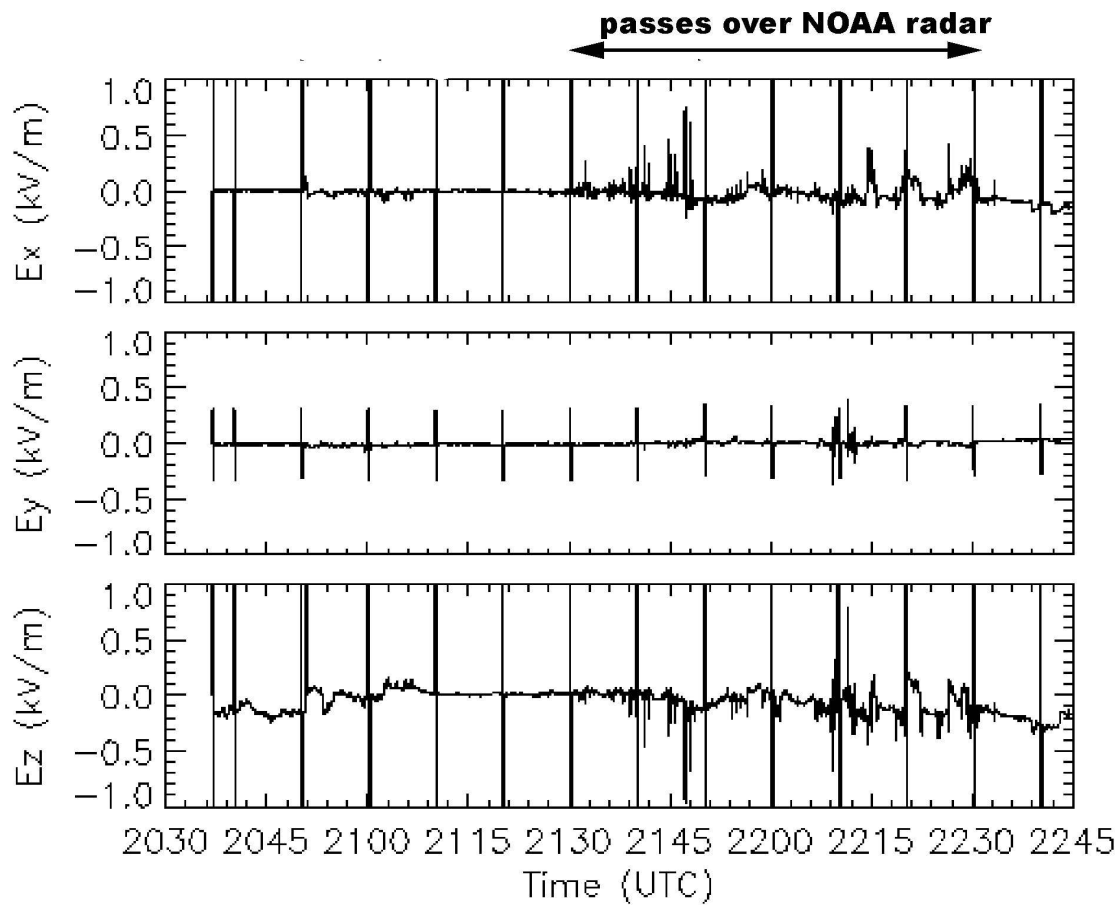


Figure 11. Electric field measurements aloft by the UND Citation, showing horizontal (E_x and E_y) and vertical (E_z) components on linear scales during the 03FEB01 flight. Vertical lines at 10-minute intervals are calibration test signals.

Discussion

The cloud mass of the 03FEB01 investigations was basically stratiform with embedded convection. In localized areas it produced virga, drizzle, or very light rain with maximum radar reflectivity of about 30 dBZ. The C-band weather surveillance radar showed that the regions of stronger echoes were loosely organized into somewhat banded patterns. The NOAA/ETL cloud radar's high-resolution data revealed that the cloud layer was about 2 km thick and its top was located approximately at the -5°C altitude, thus meeting the LLCC thick cloud rule criteria. The cloud's radar echoes included a prominent melting layer bright band, which confirms that ice crystals and/or snowflakes were present in the cloud's upper portions, and that these ice particles were melting as they fell to produce drizzle or rain drops.

In situ sampling by the UND aircraft penetrations over the cloud radar detected plentiful quantities of ice crystals and cloud droplets on each in-cloud pass above the melting level. Some of the ice particles were several millimeters in length. Thus, the cloud contained some ingredients (ice particles and supercooled water droplets) that are deemed to be important for cloud electrification, according to some theories. However, vertical motions in this predominantly stratiform cloud were weak and provided minimal dynamic means for separating charge vertically. Electric field measurements both in the air and at the ground confirmed that only very weak fields were present.

The coordinated operations and combined observations by the ABFM cloud radar, research aircraft, and electric field mills provide strong evidence that the 03FEB01 case was one in which the existing LLCC thick cloud rule would have unnecessarily prevented a launch. Of course, it is only a single case, and, for safety sake, generalizations must not be drawn from such a limited sample. Before the thick cloud rule is allowed to be relaxed or abandoned, it is important to know how often thick cloud situations pose no threat (100% of the time?, 90% of the time?), and to develop dependable ways to routinely identify the benign circumstances and distinguish them from hazardous ones. Drought conditions precluded any hope of addressing these questions from the curtailed ABFM operations in February 2001. However, 03FEB01 is one well-documented case that confirms thick-cloud-rule false alarms do indeed occur, as had been surmised by general experience of scientists at KSC. The case study also provides a more detailed knowledge of the structure and microphysical characteristics of this kind of cloud than was available previously. Many more cases are needed to determine whether this case was typical or unusual.

5. Comparisons of NOAA/K and WSR-74C Data

In addition to the ABFM case study, the NOAA/K cloud radar data have been applied to assess how well the precipitation radars used by KSC for operations are able to detect and delineate cloud layers. The up-close observations by the visiting, high-resolution and high-sensitivity ETL cloud radar can serve as a baseline for understanding the cloud observing capability of the permanent radars.

In practice, the LLCC cloud rules are assessed as well as possible by meteorologists at Cape Canaveral using scan images from the operational C-band weather radar at Patrick AFB, augmented by scan images from the National Weather Service WSR-88D radar at Melbourne, FL. Sometimes, the situation is sufficiently clear-cut from these radar images to determine that current cloud conditions violate launch commit criteria or that no cloud-related problems are present. Often, however, the scan data are inconclusive, and a reconnaissance airplane must be launched at KSC to provide *in situ* observations of clouds, winds, and other factors. Thus, timely measurements from both radar and aircraft play important roles in the launch decisions. Some aircraft launches (and hence expense) could be avoided if the radar information alone could be confidently used to make the cloud condition evaluation more often than is currently possible.

Realtime images from a C-band (5-cm wavelength) precipitation radar at Patrick AFB and S-band (10-cm wavelength) WSR-88D (NEXRAD) Doppler radar at Melbourne are routinely available for launch operations. The NOAA/K site at KSC was approximately 42 km north of the C-band radar and about 60 km north of the NEXRAD.

Comparisons on 03FEB01.

Only the clouds on 03FEB01 (discussed in Section 4) and 13FEB01 were strong enough and persistent enough for the radar comparisons with the ETL cloud radar during the ABFM's February campaign. Data from the NEXRAD were not obtained for these days, thus the following paragraphs address only the NOAA/K and WSR-74C comparisons. The NEXRAD volumetric coverage over KSC is similar to that of the WSR-74C radar (Taylor 1994).

Figures 2, 3 and 4 show examples of radar images from both radars on 03FEB01. The sensitivity and location of the ETL cloud radar directly beneath the clouds of interest, and its 37.5-m range resolution, allowed it to reveal cloud boundaries and structure with intricate detail. Furthermore, it conducted RHI scans, which are ideally suited to observing the vertical structure of clouds directly. In contrast, the C-band radar conducted its routine sequence of PPI scans, from which cloud heights and thicknesses are more difficult to determine directly, as is evident in Figure 2. However, processing software in the C-band's Sigmet processor allows vertical and horizontal cross sections to be "constructed" in near realtime from a volume of PPI sweeps. Similar software developed at NCAR (SPRINT and CEDRIC) were used in this analysis to interpolate the raw, polar-coordinate PPI scan data to a Cartesian grid, from which horizontal and vertical sections are generated. Interpolation and averaging processes involved in these constructions of cross sections inherently cause some loss of resolution and detail from the original PPI data.

The cloud radar had several other advantages over the C-band radar with regard to detecting and delineating clouds. It has excellent sensitivity and was located closer to the Cape Canaveral clouds, which allowed it to detect weaker clouds than is possible with the C-band. The 37.5-m range resolution of the cloud radar is much finer than that of the C-band radar, hence allowing cloud features to be resolved and revealed in greater detail. Furthermore, millimeter-wave

radars, such as NOAA/K, characteristically suffer less from side lobe problems that commonly cause serious problems in longer wavelength radars by smearing ground clutter contamination into high-elevation scans and exaggerating indicated cloud top heights for thunderstorms (Kropfli and Kelly 1996).

Although the radar reflectivities on 03FEB01 only reached about 25-30 dBZ, they were by far the strongest of any encountered during the drought-plagued February ABFM operations. As described in Section 4, these clouds violated the LLCC thick cloud rule. They also produced some virga, drizzle, and very light rain, which may have been sufficient to prevent a rocket launch because of precipitation conditions. Figure 12 shows horizontal sections constructed from the C-band data at 2215 UTC during the research aircraft flight. In Figure 13, vertical sections along opposing azimuths are shown for both radars. The general echo structure and reflectivity values are similar in these vertical sections, although the much coarser resolution of the C-band data is evident. The NOAA/K radar shows that cloud top was near 4.5 km above ground (as confirmed by the Citation) and had many small-scale variations. Echo top for the WSR-74C is also near 4.5 km, although a few spurious peaks extend considerably higher. Thus, in this case, the WSR-74C data were fairly good for assessing the cloud top height.

More quantitative comparisons were conducted by carefully mapping the WSR-74C volume scan data to the NOAA/K RHI scans. In these comparisons reflectivity data from NOAA/K's RHI scans along the radials that point closest to Patrick AFB (155°-335° and 185°-005° azimuth) are plotted with the nearly simultaneous data along the 350° radial from all PPI elevation sweeps of the C-band radar volume. Figure 14 shows the geometry involved in the comparisons. All data points within 19 km range of NOAA/K from these azimuths are used in the comparison.

Figure 15 shows RHI scans from NOAA/K directed toward Patrick AFB at 2052 and 2214 UTC. Unlike earlier figures, both of these images extend high enough to reveal the existence of a cirrus layer at 11-12 km AGL above the altostratus in which the Citation flew. The altostratus was much weaker at 2052 UTC than at 2214 UTC when drizzle or virga was being produced. Figure 16 shows the reflectivity-height comparisons of data points corresponding to these two times, with red points representing the cloud radar and blue squares representing the C-band precipitation radar. The cloud layer outlines are plainly revealed by the red cloud radar points. The lower layer is also evident in the blue points from C-band data at 2214 UTC and reflectivity values from both radars match well there. However, at both times the top of the lower cloud layer is uncertain in the C-band data and the existence of the weak cirrus layer is impossible to discern. Furthermore, there are numerous C-band data points of less than 5 dBZ within the cloudless region between layers. Apparently, noise and/or ground clutter extensively contaminates the C-band picture, making it difficult to discern cloud layer boundaries accurately. (Inspection of Figure 2 shows that ground clutter is prominent even in the high scans of the WSR-74C radar. The Florida coastline can be traced in all of the lower scans, and ground target echoes from the Cape area are discernable even at 16 degrees elevation). Thus data in Figure 16 indicate that the precipitation radar data define cloud boundaries over KSC fairly well where reflectivity exceeds about 5 dBZ, but may not be useful for weaker clouds.

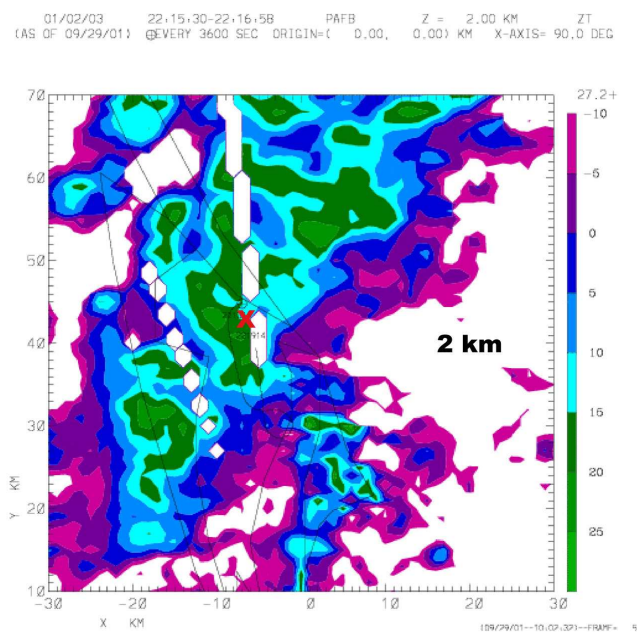
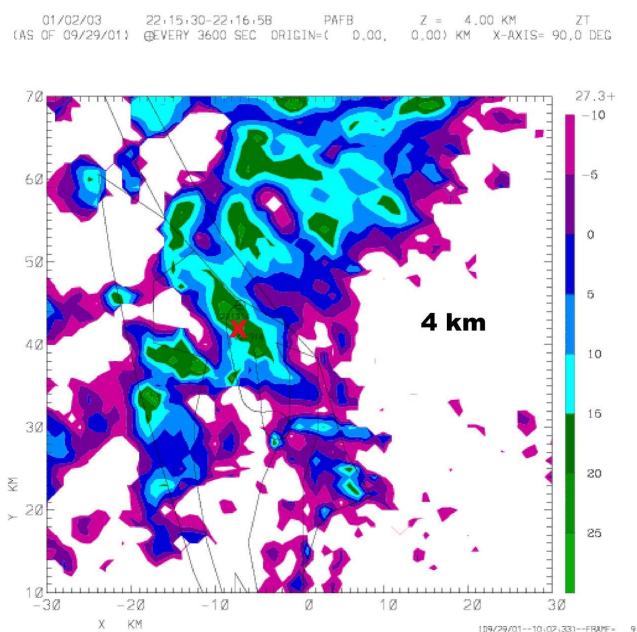


Figure 12. Horizontal cross sections of reflectivity at two altitudes constructed from a volume of WSR-74C PPI scans at about 2215 UTC. The location of the NOAA/K cloud radar is indicated by the red X.

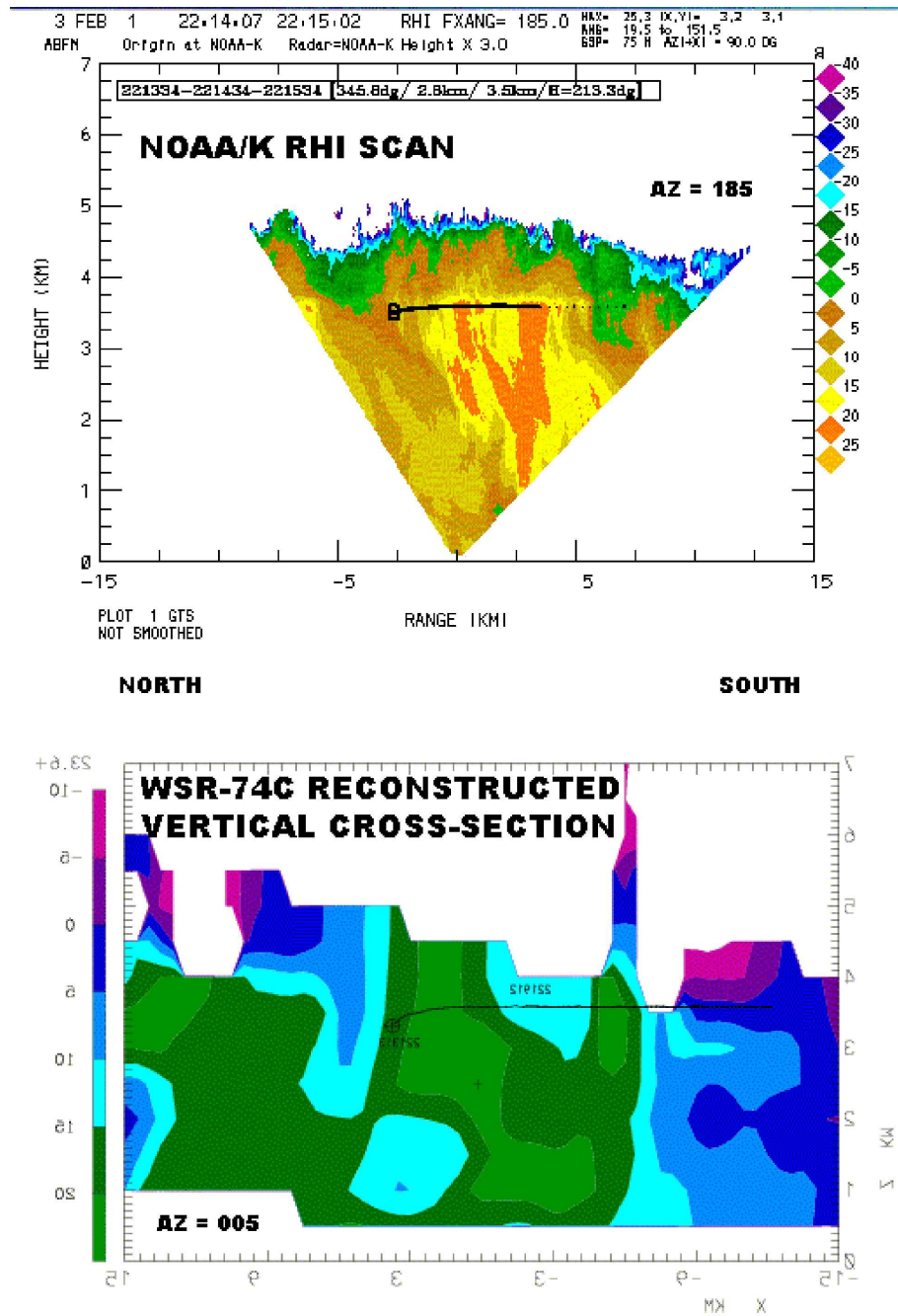


Figure 13. Vertical cross sections of radar data from approximately along the UND Citation track at 2215 UTC. Upper panel is an RHI scan from NOAA/K. Bottom panel is a vertical section constructed from a volume of PPI scans by the WSR-74C. The horizontal scale of the bottom panel is intentionally reversed to match the orientation of the NOAA/K scan. The aircraft flight track is shown as curved black line.

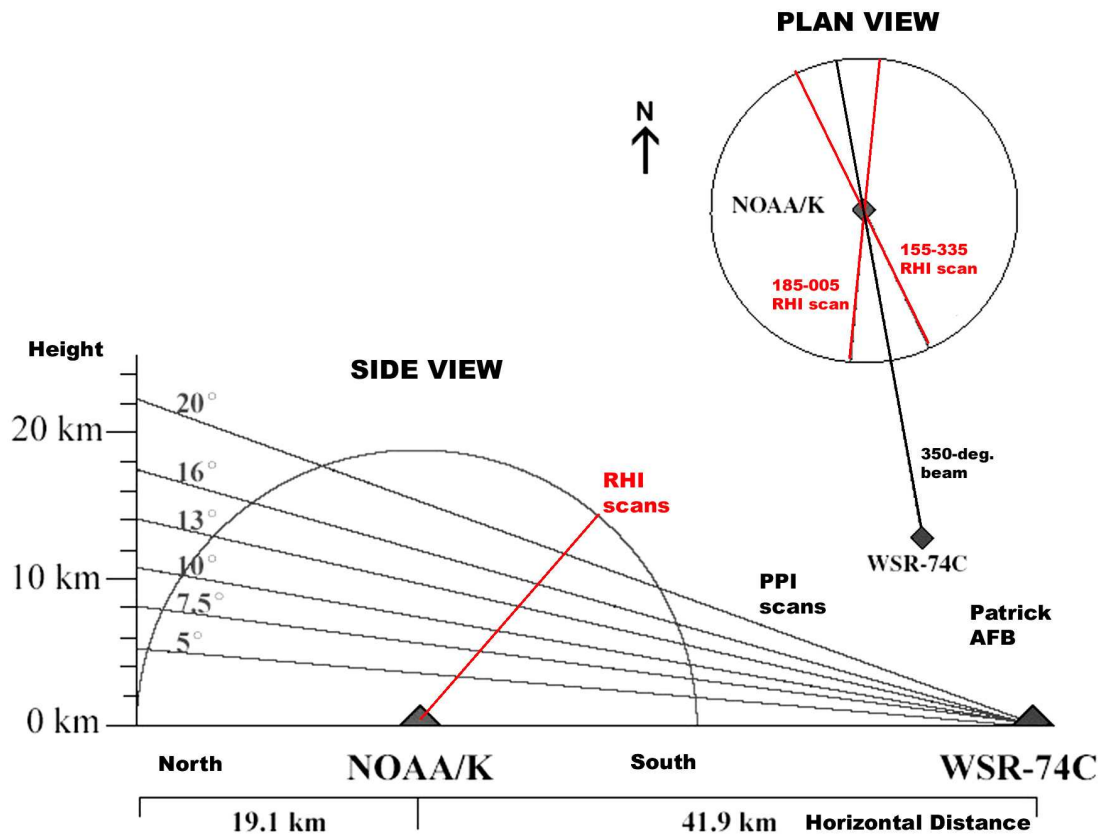


Figure 14. Plan view and side view diagrams showing the geometry involved in the comparisons of data from the NOAA/K cloud radar at KSC and the WSR-74C precipitation radar at Patrick AFB. Comparisons were made within the 19-km-radius hemisphere over NOAA/K, using data along the azimuths shown in red and black on the plan view. The NOAA/K data were from RHI scans and the WSR-74C data points were extracted from PPI scans conducted at approximately the same time.

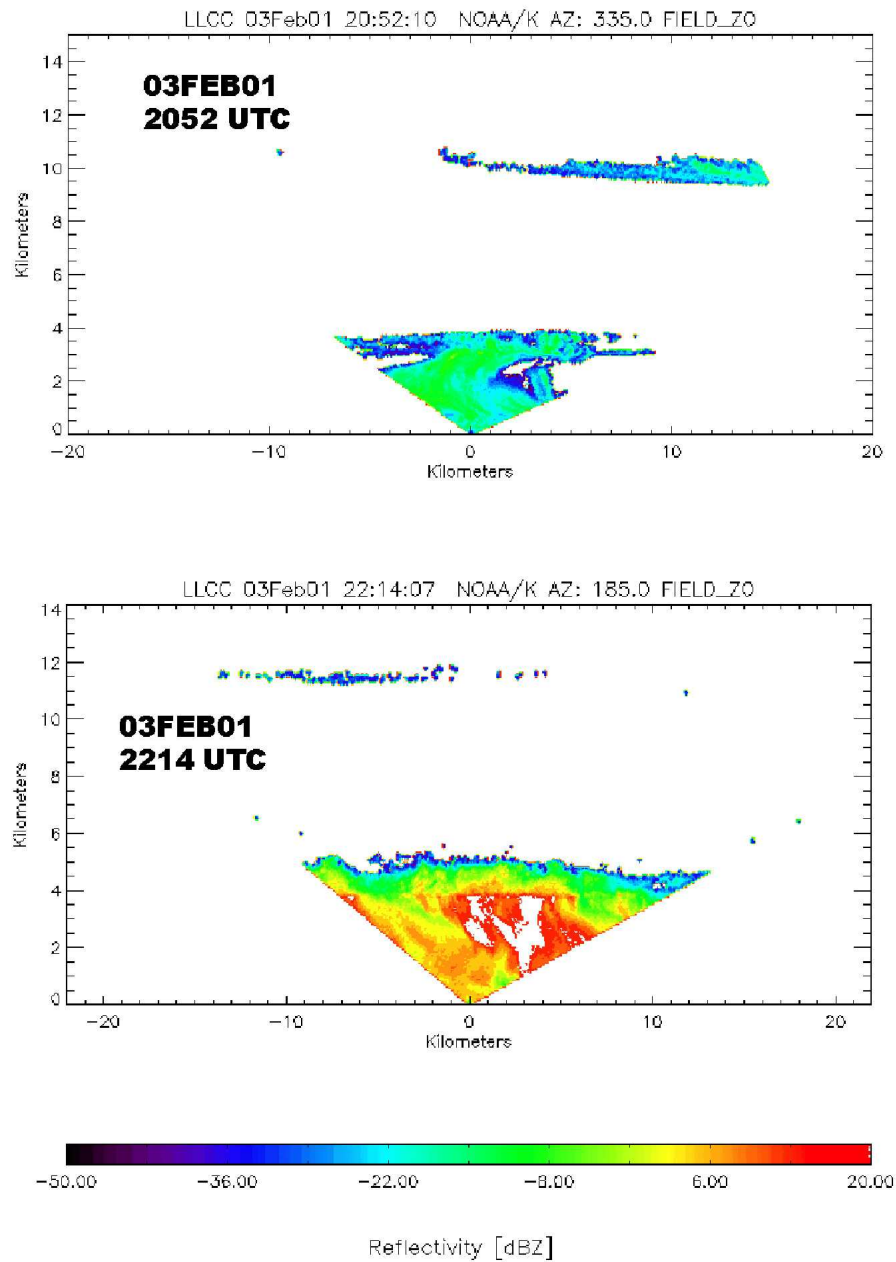


Figure 15. RHI scans from the NOAA/K cloud radar at 2052 and 2214 UTC on 03FEB01 showing the lower clouds that were the subject of the aircraft penetrations and a weak overlaying cirrus layer. These scans were directed approximately north-south.

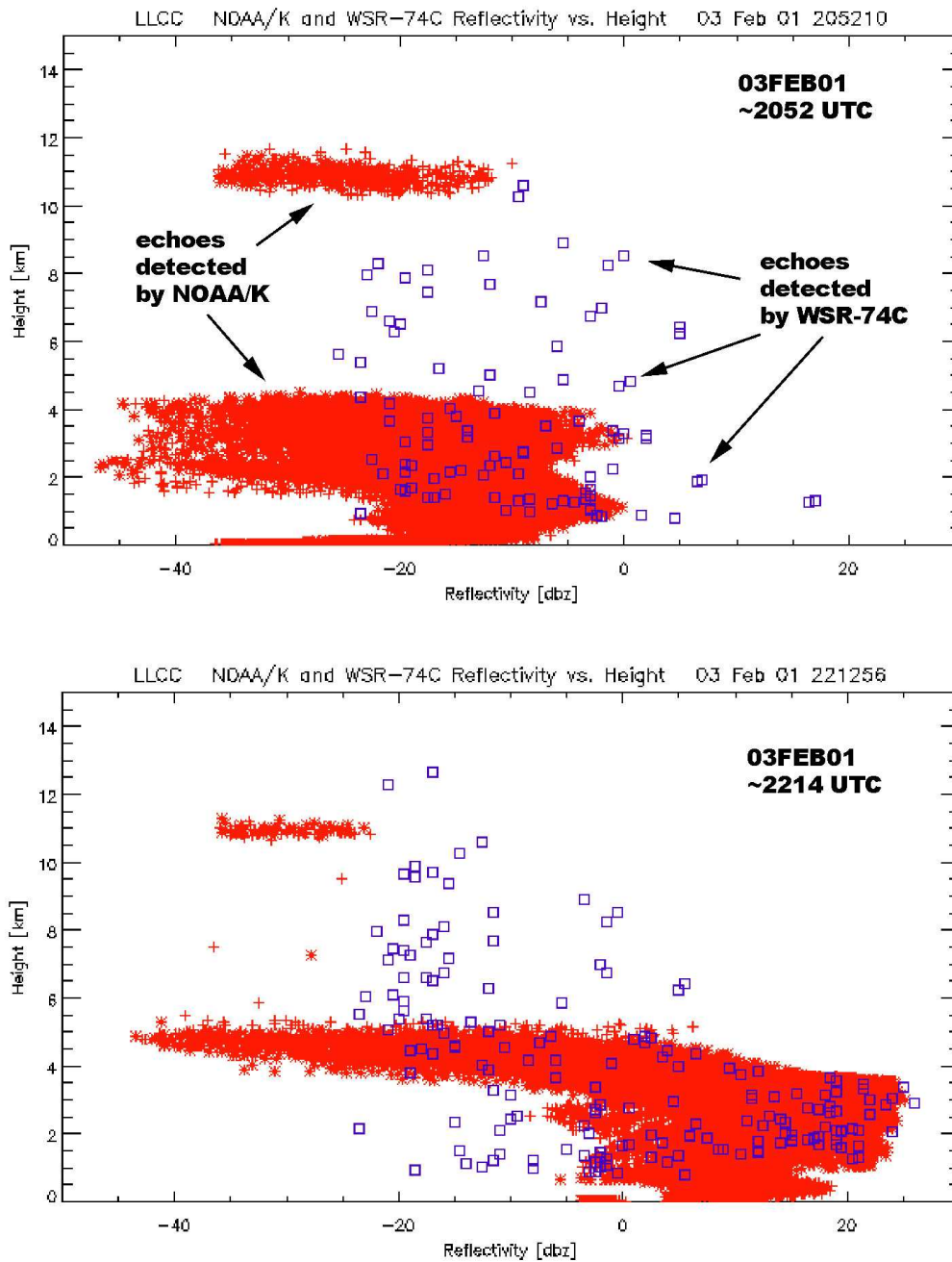


Figure 16. Reflectivity data as a function of height from RHI scans of the NOAA/K cloud radar (red points) and from PPI scans of the WSR-74C precipitation radar (blue squares) for two times on 03FEB01. The selected times and range gates for the two radars are as coincident as possible, as explained in the text.

Comparisons on 13FEB01.

Similar comparisons were made for 13FEB01. On this day very thin stratus overcast with occasional ground fog was intermittently overlain by one or two cirrus layers, according to the cloud radar observations. The cirrus was not associated with a thunderstorm anvil. These were extremely weak clouds (10 dBZ maximum reflectivity) and would probably not be considered to be any kind of lightning threat. However, they do present another test, and a demanding one, of how well the C-band radar is able to detect non-precipitating clouds.

Figure 17 shows PPI scan images from the Patrick AFB C-band radar at approximately 1744 UTC on 13FEB01. The cirrus layer is partially detected as a broken ring of echo north and northeast of Patrick AFB in the higher scans, and there is a hint of echo from stratus to the southwest in the lowest scan. The situation is clarified greatly by the NOAA/K cloud radar data, as shown in its images at 1611 UTC, 1742-1752 UTC, and 1833-1843 UTC in Figure 18. The first (top) image is from an RHI scan and the latter two are time-height images for 10-minute periods when the radar was pointing at the zenith. The reflectivity-height comparison plots for these three times are shown in Figure 19. The red points from the cloud radar clearly delineate the weak cirrus layers, in which the reflectivities were less than about 0 dBZ at these times. The even weaker stratus (< -20 dBZ) is also evident, although there are a few points above it in the cloud radar data that are probably echoes from insects.

In contrast, the blue points in Fig. 19 from the C-band radar data are apparently dominated by clutter or noise and provide no clear indication of any cloud layer boundaries, and even the existence of the thicker cirrus layer is only suggested. Thus, the radar used in operational LLCC decisions is not capable of delineating cloud layers as weak as these. This is not necessarily bad, if these very weak clouds can be confidently discarded as purely benign. However, the dramatically enhanced cloud depictions available from a cloud radar definitely offer more comprehensive, detailed, and reassuringly precise information about existing cloud conditions.

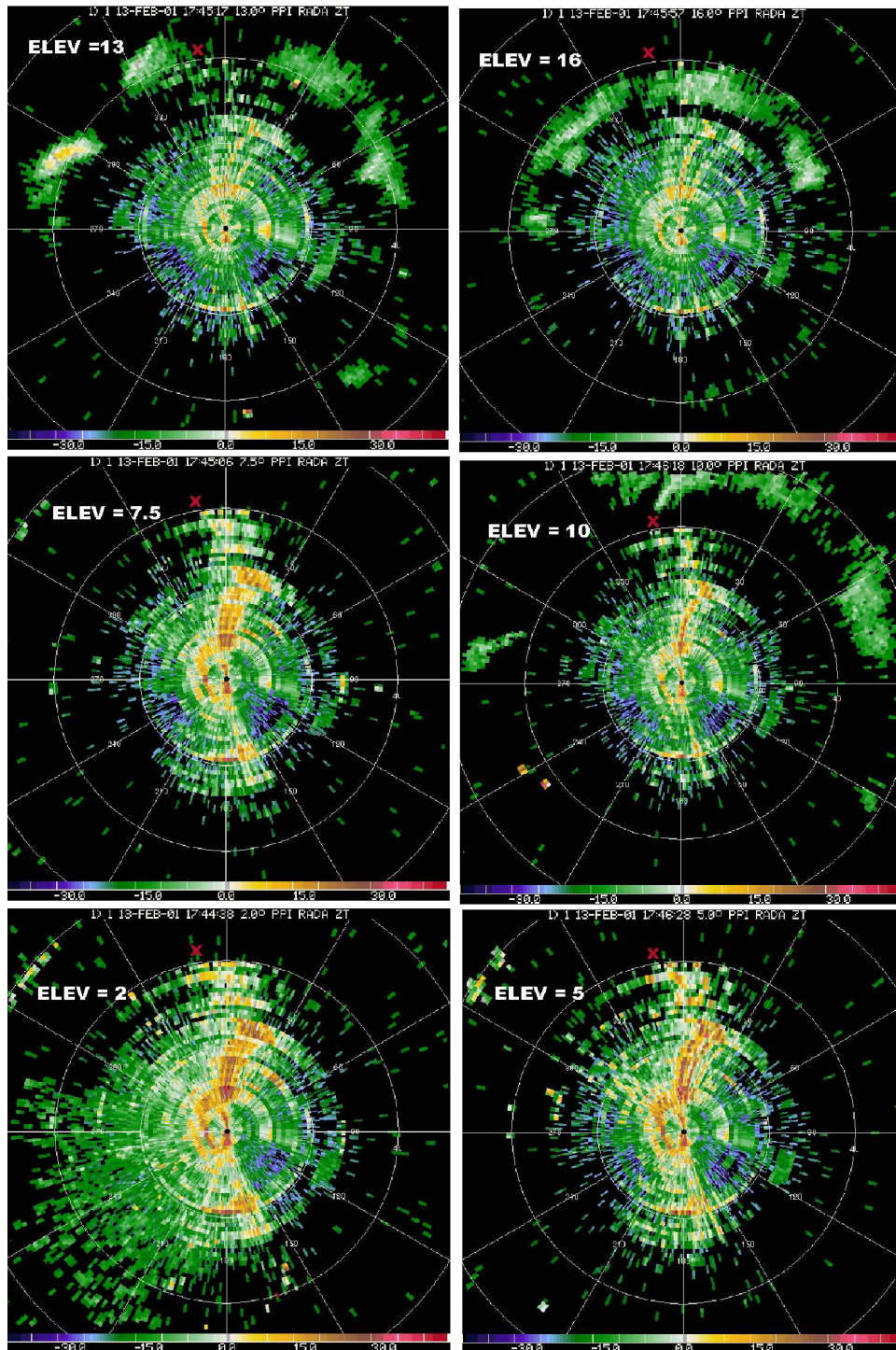


Figure 17. PPI images of reflectivity from six elevation-angle scans of the WSR-74C radar at approximately 1744 UTC on 13FEB01. Range rings are drawn at 20-km intervals. The location of the NOAA/K cloud radar at azimuth = 350 deg. And range 42 km is indicated by the red X.

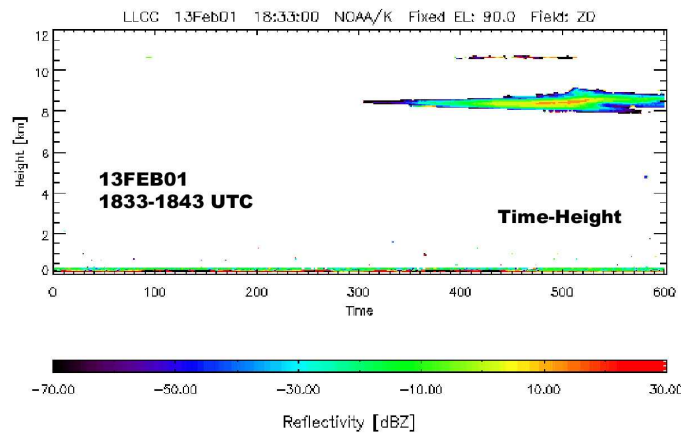
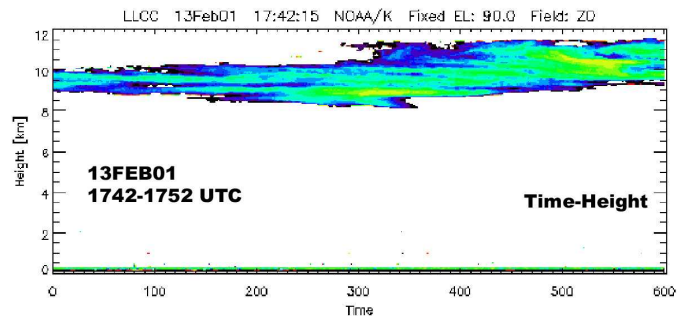
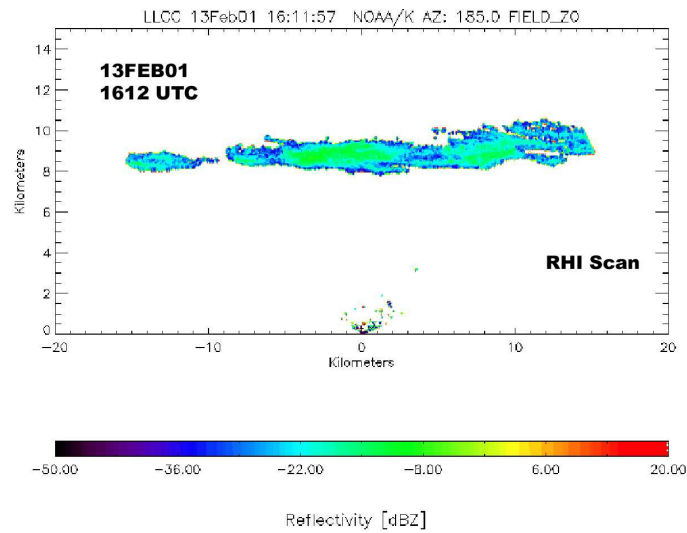


Figure 18. Reflectivity images from the NOAA/K cloud radar for three times on 13FEB01. The top panel is the image from an RHI scan. The two lower panels are 10-minute time-height images from periods when the antenna was pointed continuously at the zenith.

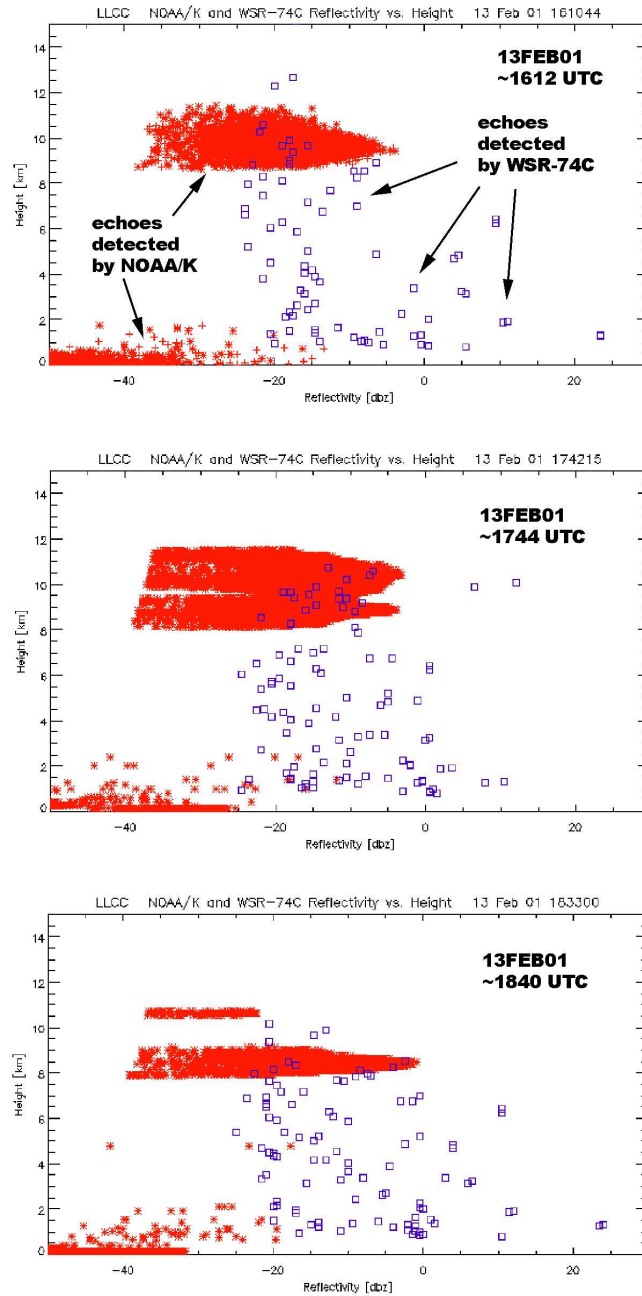


Figure 19. Reflectivity data as a function of height from the NOAA/K cloud radar (red points) and from PPI scans of the WSR-74C precipitation radar (blue squares) for three time periods on 13FEB01. NOAA/K data are from RHI scans in the upper panel and from vertically pointing observations in the lower two panels. The selected times and range gates for the two radars are as coincident as possible, as explained in the text.

6. Summary and Conclusions

A high-sensitivity, high-resolution, millimeter-wave cloud radar was operated at KSC as part of the ABFM experiment in February 2001. The radar was the 35-GHz NOAA/K system from NOAA/ETL, which has scanning, Doppler, and dual-polarization capabilities, and is capable of detecting most non-precipitating clouds in its nearby area with 37.5-m spatial resolution. Stringent KSC frequency management rules were accommodated in the NOAA/K operations. Two objectives related to lightning launch commit criteria (LLCC) were to be served by this instrument in the ABFM. A primary intended use was detailed documentation of cloud structure, within the context of which, concurrent research aircraft and ground-based electric field mill measurements could be better interpreted to study cloud electrification processes. Assessment of the LLCC “thick cloud” rule was of particular interest in these studies. A second goal was to use the cloud radar as a “ruler” for assessing capabilities and limitations of the permanent precipitation radars in the area for detecting cloud layers and measuring their heights and thicknesses. In this way, it was hoped that the routine data from these radars could be used with greater confidence in the future for operational LLCC decision making.

Unfortunately, the February 2001 ABFM operations took place during the height of one of the worst droughts in Florida’s history, and precipitation and clouds were exceptionally scarce. Thus, ABFM objectives were not met. However, some useful data were obtained for the thick cloud rule investigation and for the cloud radar / precipitation radar comparisons. These observations are only anecdotal indicators of KSC conditions, because climatological representativeness cannot be determined from the minimal number of cases in February 2001. Nevertheless, the NOAA/K radar data constitute the most detailed radar observations of cloud structure and kinematics obtained to date at KSC, and are therefore worthy of analysis. The data also demonstrate some of the potential usefulness of millimeter-wave radar for rocket range operations, which is a consideration for future generations of range observational networks.

The only research aircraft flight over the cloud radar took place on 03FEB01 in a mid-level stratiform cloud that occasionally produced virga, drizzle and very light rain. Based on realtime imagery from the cloud radar the University of North Dakota Citation was launched and conducted 18 in-cloud passes over the radar at levels ranging from approximately -5 °C to +1 °C. The cloud radar showed that the cloud layer was about 2 km thick and exhibited a prominent melting layer bright band. Therefore, the cloud radar data alone, as well as in combination with the aircraft in-situ measurements, establish that this cloud met the thickness and temperature conditions to qualify as an LLCC thick cloud rule case. (It may have also qualified as an LLCC precipitation case). The aircraft particle sampling showed that the cloud contained liquid water droplets and ice crystals, and a few centimeter-size snowflakes. The radar’s depolarization ratio measurements also indicated the presence of ice crystals diluted with coexisting water drops above the melting layer, and showed the definite signature of water drops below the melting layer. Both the ground-based and airborne electric field mills recorded only very weak electric field strengths that were generally less than 300 v/km. Thus, although this cloud met the thick cloud rule criteria, it posed little or no threat of triggered lightning. Furthermore, no natural

lightning strikes occurred anywhere in central Florida on this day. The implication of these observations is that the LLCC thick cloud rule was overly conservative *in this particular case*.

Comparisons of the cloud radar observations with those of the C-band precipitation radar that is used operationally by KSC for launch decisions were made for clouds on two days. The cloud radar at KSC conducted RHI scans through the clouds overhead while the precipitation radar at Patrick AFB conducted a volume of PPI scans. Radar echoes from the altostratus cloud and drizzle on 03FEB01 reached maximum values of 25-30 dBZ. In contrast, reflectivities were generally less than 0 dBZ in cirrus and stratus clouds on 13FEB01. The superior spatial resolution of the cloud radar data was obvious as it revealed intricate cloud features that were not resolved by the C-band radar. Agreement on general features including cloud top height was fairly good on the stronger case of 03FEB01, for which the C-band data would have been reasonably dependable for judging the thick cloud rule. However, the cloud radar provided much better precision. An overlying weak cirrus layer on this day was detected by the cloud radar but missed by the precipitation radar. The much weaker non-precipitating cloud layers detected by the cloud radar on 13FEB01 were very difficult to discern in the C-band radar data or were entirely undetected.

On both days the NOAA/K cloud radar was able to detect much weaker portions of the clouds. Cloud boundaries on all cases were more difficult to delineate in the C-band data because of a considerable degree of noise or ground clutter contamination even at higher elevation angles. Based on this very limited two-day sample, it appears that the C-band radar at Patrick AFB is probably not useful for accurately delineating cloud heights and thicknesses over KSC, unless reflectivities exceed about 5 dBZ. Perhaps clouds weaker than this pose no threat of triggered or natural lightning. However, in the case of liquid water stratus, they could certainly be optically dense enough to inhibit launches based on visibility concerns.

Currently, KSC intends to do the best it can at assessing cloud conditions for launch decisions using the available operational precipitation radar data, augmented whenever necessary by aircraft soundings. However, it is clear from the very limited ABFM experience and from a wealth of deployments in other research programs, that cloud radars, although expensive, could be valuable tools for rocket range operations in the future. The NOAA/K operations in the ABFM helped to clarify benefits and concerns in this regard.

One concern met head-on in the ABFM was the frequency management regulations for millimeter-wave transmitters. NOAA/K is a high-power (80 kW) cloud radar. In retrospect, most or all of the frequency management restrictions could have been avoided by using a low-power cloud radar, such as ETL's vertically pointing Millimeter-wave Cloud Radar (MMCR) Package described by Martner et al (2002b). This 35-GHz radar achieves superb sensitivity that exceeds that of NOAA/K, while transmitting only 0.1 kW of peak power. Although it does not scan, the MMCR provides excellent profiling of tropospheric clouds overhead and it is designed to operate continuously and unattended in a manner similar to wind profilers. Thus, at the expense of foregoing scanning observations of the horizontal distribution of clouds over the

Cape, the MMCR would avoid the stringent 1 v/m threshold problem because it transmits about 30 dB less power than NOAA/K and it only points straight up. It is housed in a 20-ft sea container along with vertically-pointing radiometers. In combination, the radar and radiometers provide estimates of the mass content, median size, and total concentration of ice and liquid water hydrometeors as a function of height, as well as continuous measurement of precipitable water vapor and liquid water path overhead. The technology to operate such a package as a long-term, automated installation has been demonstrated in the MMCRs designed by ETL for the U.S. Department of Energy's Cloud and Radiation Testbeds (Moran et al 1998). This package provides a highly accurate anchor-point profile of detailed information on cloud properties aloft that might be very valuable for rocket range operations.

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Appendix

Table A1. NOAA/K Cloud Radar Data Tapes and Recording Periods for the 2001 ABFM.

TAPE			
NO.	DATE	TIME (UTC)	COMMENTS
012	01FEB01	1650-1956	tests with some stratus, cirrus
101	02FEB01	1905-2129	stratus and other low layers
102	03FEB01	1337-2244	stratus, drizzle & thick midlevel cloud with Citation flight
103	05FEB01	1415-2125	altocu briefly and persistent cirrus
104	10FEB01	1523-2300	weak cirrus all day
105	11FEB01	1412-2100	some stratus and day-long cirrus
106	13FEB01	1523-2047	variable cirrus and stratus/fog
107	17FEB01	1315-2300	cirrus, low frontal clouds, smoke
108	21FEB01	1650-2029	cirrus
109	22FEB01	1409-1431	clear, sunplot

UTC = EST + 5 hr

All tapes are archived at NOAA/ETL on 8-mm media cartridges in three formats:

Raw

Common Doppler Radar Exchange (“universal”)

netCDF.

NOAA/K Radar Site Location:

latitude = 28.6257 deg. N

longitude = 80.6833 deg. W

altitude ~ 3 m MSL

KSC facility site: J6-407 (adjacent to C-band tracking radar)